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Pesticide residues in animal feed: A hidden threat to livestock health and food safety

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Abstract
Pesticides are chemical substances use to control pests, weeds and several diseases in agriculture, enhancing crop yield and food security. Globally, pesticide use has reached approximately 3.70 million tonnes annually, saving crops worth four times the cost of application. However, over 95% of applied pesticides miss their target, contaminating soil, water and animal feed. Their extensive use has led to unintended consequences, particularly the persistence of residue for several years in soil, air and water. Residues in livestock feed led to bioaccumulation in milk, meat and eggs causing reproductive, neurological and immunological disorders. In India, more than 100 pesticides banned including DDT but are still in use, with widespread detection in animal-origin foods. While regulatory systems exist, gaps remain in monitoring and in setting defined residue limits for animal feed. This review emphasizes the need for safer alternatives such as biopesticides and improved residue mitigation strategies to ensure both animal well-being and food safety.

Keywords: Pesticides, residues, bioaccumulation, food safety, livestock, biopesticides

1. Introduction
Pesticides play a crucial role in modern agriculture by protecting crops and livestock from pests, diseases and weeds thereby improving yield, quality and reducing production costs (Hassaan and El Nemr, 2020) [14]. They include insecticides, herbicides, fungicides and rodenticides, that have been widely used in agriculture since 20th century. India is currently Asia's 2nd largest pesticide producer after China and ranks 12th globally in consumption (Kalyabina *et al.*, 2021) [16]. Global pesticides usage has now reached approximately 3.70 million tonnes per year out of which herbicides are (52.63%), fungicides and bactericides (21%), insecticides (20.93%) and other classes (4.93%) (FAO, 2018) [12].
Pesticides significantly reduced crop losses up to 78% in fruits, 54% in vegetables and 32% in cereals and support food security (Tudi *et al.*, 2021) [25]. It is estimated that for every dollar ($1) spent on pesticides, crops worth four dollars ($4) are saved (Neff *et al.*, 2012) [23]. The consumption of pesticide in India is about 600 g/hectare, while in developed countries is 3000 g/hectare, still the problem of pesticide residue is very high in India due to environmental persistence (Kalyabina *et al.*, 2021) [16]. In India, number of registered pesticides is 293 and around 104 pesticides being using in India that are prohibited in one or more nations in the world. Among all the pesticides, chlorpyriphos is the most commonly used in India followed by cypermethrin, malathion and acephate. The main use of pesticides in India is for cotton crops (45%), followed by paddy and wheat (Hassaan and El Nemr, 2020) [14].
However, over 95% of sprayed pesticides fail to reach their target, instead contaminating soil, air and water (Roser and Ritchie, 2017) [24]. Improper use of pesticides leads to accumulation of pesticide residues in food crops as well as in livestock feed ingredients. These residues can enter animal body through contaminated feed and bioaccumulate in tissues and animal products like milk, meat and eggs thus poses threat to both animal and human health (EFSA, 2020) [1] such as reproductive failure, immunosuppression, reduced growth and metabolic disorders. Moreover, through biomagnification, these residues level in animal products exceed Maximum Residue Limits (MRLs), thereby violating food safety standards (Codex Alimentarius, 2021) [6].

developing countries, number of deaths of people due to pesticide consumption in food every year is approximately 20,000 (Bhardwaj and Sharma, 2013) [4].

However, growing concerns about the environmental persistence and health hazards of pesticides have led to increased interest in safer and more sustainable alternatives such as Integrated Pest Management (IPM), biopesticides, crop rotation and precision farming. In recent years, global market for biopesticides and botanical products has been expanding, offering eco-friendly options to mitigate adverse effects of synthetic chemicals on both ecosystems and human health (Duke *et al.*, 2022) [10].

2. Historical background of pesticides

The history of using pesticides to control pests is more than 4000 years old to the times of ancient Romans where people used to burn sulphur for killing pests and used salts and ashes for controlling weeds (Mahmood *et al.*, 2016) [22]. By the 15th century, more toxic substances like arsenic, mercury and lead were applied to plants to kill pests (Deadman, 2017) [8]. A major historical milestone occurred in 1867, where an impure copper arsenite mixture was used in the United States to control a serious outbreak of the Colorado potato beetle—marking the transition from traditional to chemical pest control practices. The next major step came with the synthesis of DDT in 1874. In the 1970s, safer classes of insecticides like organophosphates and carbamates began replacing organochlorines, due to their harmful environmental effects. Despite this evolution, traditional agents such as sulphur dust and copper-based sprays like Bordeaux mixture still in use today, particularly in organic agriculture (Deadman, 2017) [8].

3. Definition of Pesticides, Uses and Emerging Concerns

Pesticides (Latin: pestis-plague, occido-kill), i.e., plant protection products, belong to a group of chemical compounds with a high toxic effect (FAO, 2018) [12]. They may be natural, organic or synthetic origin**,** include variety of chemical classes such as insecticides, herbicides, fungicides and rodenticides (Tudi *et al.*, 2021) [25]. The primary objective includes protecting crops and livestock from pests, diseases and weeds, thereby improving yield, quality and reducing production costs (Hassaan and El Nemr, 2020) [14]. They also help to control vectors of human and animal diseases like malaria and dengue, that supports public health. Economically, pesticides increase farmer's income by minimizing crop loss and enhancing storage longevity (Neff *et al.*, 2012) [23]. Beyond agriculture, they also used in household pest control**,** wood preservation and sanitation programs (Kalyabina *et al.*, 2021) [16]. However, the indiscriminate and prolonged use of pesticides often above MRLs, has raised serious environmental and food safety concerns. Residues from these chemicals have been consistently detected in animal feed, fodder and crop products**,** indicating a widespread contamination of food chain (Aulakh *et al.*, 2006) [1].

A major concern is the non-selective toxicity of many pesticides. These compounds not only eliminate target pests but also affect beneficial insects, soil microbes, aquatic organisms and terrestrial wildlife**.** Some pesticides are known to persist in the soil and water for years**,** leading to bioaccumulation and biomagnification in ecosystems (Deti *et al.*, 2014) [9].

4. Common Pesticides Detected in Animal Feed

Table 1: Summary of Common Pesticides in Animal Feed (EFSA, 2020) [1]

Pesticide Class	Representative Compounds	Feed Sources	Health Impacts	Remarks
Organo-chlorines	DDT, Endosulfan, Lindane, Aldrin	Oilcakes, oilseed residues, green fodder	Reproductive disorders, Neurotoxicity, bioaccumulation in fat and milk	Banned but persistent
Organo-phosphates	Malathion, Diazinon, Chlorpyrifos	Cereal grains, Green fodder, Processed feed	Neurotoxicity, Acetylcholin-esterase enzyme inhibition	Widely used, milk transfer reported
Carbamates	Carbaryl, Aldicarb, Propoxur	Forage crops	Acute toxicity, tremors	Less stable than OCPs
Pyrethroids	Cypermethrin, Deltamethrin	Stored feed	Tremors, skin and mucosal irritation	Residues found in commercial feed
Herbicides/Fungicides	Atrazine (herbicide), Mancozeb (Fungicides)	Fodder, silage (maize and wheat)	Hormonal and liver effects	Rarely monitored in feed

5. Pesticide residues in animal products

Animal products including milk, meat and eggs, contain residues because food-producing animals ingest polluted animal feed (Kumar *et al.*, 2012) [19].

In egg

Pesticides are transmitted through feed, water and air into poultry and residues appear in eggs (Zhou *et al.*, 2018) [29]. But, poultry feed has been identified as a major source of egg contamination. The yolk, being lipid-rich, retains higher residue concentrations than albumen. At the most recent FAO/WHO joint meeting, it was recommended that pesticide MRLs in shell-free eggs should not exceed 0.2 mg/kg (WHO, 2021) [27].

In meat

Residues concentration in meat is influenced by animal origin, dipping practices or consumption of contaminated feed, these all results into high amounts of pesticide residues in meat. Beef samples have shown alarming levels of DDT, sometimes exceeding 400 µg/kg in fat tissues (Darko and Acquaah, 2007) [7].

In Milk

Pesticide residues and metabolites can be detected in milk as a consequence of using pesticides to treat ectoparasites directly on the animal, consuming contaminated pastures or feed and water (Bajwa and Sandhu, 2014) [3]. In lactating animals, particularly dairy cows and buffaloes, milk fat acts as a primary carrier for such residues.

5.1 Sources of pesticide residues in food and animal Products

1. **Contamination during crop production:** When Pre-harvest intervals (PHIs) are not strictly followed, residues persist in the harvested material. Chlorpyrifos,

Carbaryl and Cypermethrin are commonly detected in such crops.

2. **Post-Harvest Treatment and Storage:** After harvest, crops are often stored in warehouses or silos where they treated with fumigants and insecticides to prevent pest infestations, if directly fed to animals leads residue transfer to animals body. Chemicals such as malathion, aluminium phosphide and deltamethrin are routinely used here.
3. **Environmental Contamination:** Crops irrigated with pesticide-contaminated water or grown in polluted soils can absorb these chemicals systemically, leading to residue presence even in green fodder and silage (EFSA, 2020) [1]. Improper waste disposal practices near agricultural land further amplify contamination load in forage crops.
4. **Other sources:** Unapproved or excessive use of pesticides in fodder crops and direct application of insecticides on animals body to control parasites, leads to residue transfer to the plants and animals body. Occupational, agricultural and dietary exposures are also common in human, especially in India where about 56.7% of the population is engaged in farming (Neff *et al.*, 2012 and WHO, 2021) [23, 21].

5.2 Localization of Pesticide Residues in Food Commodities

The localization of pesticide residues in food depends on both the chemical properties of the pesticide and the nature of the food. In fruits and vegetables, residues mainly remain on the peel and can often be removed by washing, peeling or chemical treatments with vinegar, turmeric, sodium bicarbonate, common salt or alcohol (Awasthi, 1993 and Gupta 2006) [2, 13]. In fruits and fruit-type vegetables, the concentration of pesticide residue remain higher in the fruit stalk and near the epidermis than in the sarcocarp or pericarp (Bajwa and Sandhu, 2014) [3]. In leaf vegetables, concentration of pesticide residue was higher in outer leaves than in inner ones (Yoshida *et al.*, 1992) [28]. In cereal grains, most residues concentrate in outer layer of grain i.e. bran and milling can reduce levels in flour (Udeaan and Bindra, 1973) [26]. In pulses, certain pesticides like cypermethrin resist removal by washing or cooking, indicating internal absorption and its maximum concentration found on seed coats (Hazarika and Dikshit, 1992) [15]. Milk, dairy products and meat often retain residues in fat-rich portions due to contaminated feed (Li *et al.*, 1970) [21]. In eggs also, lipid-soluble pesticides are found in higher amounts in egg yolk while water-soluble ones are higher in albumin (Krieger, 2001) [18].

6. Impact of pesticide residue on Livestock Health

1. **Reproductive Disorders:** Reproductive efficiency is significantly affected by chronic ingestion of pesticide-contaminated feed. Subclinical impacts such as delayed estrus, silent heat, reduced conception and poor semen quality often go unnoticed but result in extended calving intervals and increased insemination costs. Pesticide exposure during pregnancy is associated with increased risk of spontaneous abortion, foetal death and childhood cancers such as acute lymphocytic leukemia.
2. **Immunotoxicity:** Chronic exposure to compounds like DDT, endosulfan impairs both humoral and cell-mediated immunity in livestock. These pesticides disrupt immune cell function by inducing oxidative stress, damaging lymphoid organs (e.g., thymus, spleen) and altering cytokine expression. This suppression leads to increased risk to infections, vaccination failure and higher morbidity in calves, poultry and periparturient dairy animals.
3. **Neurological Effects:** Organophosphates causes acetylcholinesterase (AChE) inhibition which leads to accumulation of acetylcholine at synapses, causing neuromuscular overstimulation**,** causes muscle tremors, hypersalivation, incoordination and convulsions**.** In chronic low-dose exposure, signs may include decreased feed intake, altered behaviour, reduced milk letdown reflex and lethargy especially in high-yielding dairy cows and poultry.
4. **Hepatic and Renal Toxicity:** The liver and kidneys**,** being central organs for xenobiotic metabolism and excretion, are highly damage from chronic pesticide exposure in livestock. Pesticide degradation in liver causes generation of reactive intermediates that induce oxidative stress**,** lipid peroxidation and cellular damage. Also affect kidney functions by imparing filtration and excretion**,** leading to systemic toxicity.
5. **Metabolic and Endocrine Effects:** In pregnant and lactating animals, metabolic stress from pesticide exposure can lead to ketosis, milk fever and reduced milk production, due to impaired hormonal responses (e.g., insulin, cortisol).

7. Maximum Residue Limits (MRLs) and toxicity

MRLs are defined as the upper legal limits of pesticide concentration (in mg/kg) in food or feed, based on good agricultural practices and to ensure the lowest possible consumer exposure (Neff *et al.*, 2012) [23]. These limits are determined based on toxicological data**,** acceptable daily intake (ADI) and risk assessment models to ensure consumer safety over a lifetime exposure. It is illegal to sell, import or export products with residues above the established MRLs (Deti *et al.*, 2014) [9].

Note: It is important to note that each country has the autonomy to setting MRLs values

Toxicity Parameters

Toxicity data obtained from animal trials include lethal concentration (LC_{50}) and lethal dose (LD_{50}), used for pesticide classification.

Table 2: Classification of pesticides according to the degree of toxicity (WHO, 2021) [27]

Class	Toxicity	Colour
I	Extremely toxic	Red
II	Highly toxic	Yellow
III	Moderately toxic	Blue
IV	Slightly toxic	Green

[These categories (Class I-IV) are labeled on pesticide containers]

8. Regulation of Pesticides

The Food Safety and Standards Authority of India (FSSAI) oversees MRLs in food products of animal origin, while the Central Insecticides Board and Registration Committee (CIBRC) under the Ministry of Agriculture is responsible for pesticide registration, safe use guidelines and residue monitoring in crops and fodder. The Prevention of Food

Adulteration Act, along with the Food Safety and Standards Act (2006), provides legal framework to control pesticide contamination. However, MRLs for animal feed are still not well defined or consistently monitored, despite being a primary entry point for pesticide residues into the food chain. In India, institutions like ICAR-NRC on Residue Monitoring, Export Inspection Agencies (EIA) and state food safety departments conduct random sampling and testing.

In the late 1960s, a new arena was opened in which "Integrated pest management" (IPM) was introduced, in which biological predators or parasites are used for controlling the pests (Mahmood *et al.*, 2016) [22]. 179 nations including India signed an international treaty in 2001 (Stockholm Convention) that was intended to completely ban 12 Persistent Organic Pollutants (POP's) including DDT (Mahmood *et al.*, 2016) [22]. This convention has classified most of the organochlorines as environmental hazards because of persistence and bioaccumulation effect and banned their use. In India, FSSAI vide Food Safety and Standards (Contaminants, Toxins and Residues) Regulations, 2011 has established tolerance limits for various food commodities such as milk, meat, egg, fish, water, food grains, pulses, vegetables, fruits etc., but still such limits for animal feed materials have not yet been set in India (Kumar *et al.*, 2019) [20]. In spite of ban, DDT and Benzene hexachloride (BHC) are still in production in India and are being detected in many matrices. Out of their total production in world, India manufactures 77% DDT and 95% BHC (Chauhan and Singhal, 2006) [5].

Table 3: List of pesticides banned in India

Alachlor	Dichlorvos	Nitrofen
Aldicarb	Ethylene dibromide	Paraquate Dimethyl Sulphate
Aldrin	Ethyl mercury chloride	Pentachloro nitrobenzene (PCNB)
Benzene Hexachloride (BHC)	Ethyl Parathion	Pentachlorophenol (PCP)
Benomyl	Fenarimol	Phorate
Calcium cyanide	Heptachlor	Phosphamidon 85% SL
Captafol 80% Powder	Methoxy ethyl Mercury Chloride (MEMC)	Sodium Methane Arsonate (MSMA)
Carbaryl	Methyl parathion	Sodium cyanide
Chlordane	Maleic Hydrazide	Tetradifon
Chlorobenzilate	Menazone	Toxafen
Cibromochloropropan	MehtomyI 12:5% L	Thiometon
Dieldrine	Mehtomyl 24% L	Trichloro acetic acid (TCA)
Endrin	Nicotine sulfate	Tridemorph

Source: Government of India Gazette Notification (2003 and 2016)

Table 5: List of detected pesticide residue

Items	Pesticide residue detected
Soil and water	Permethrin, cypermethrin, fenvelerate, deltamethrin, DDT, Aldrin, BHC, Heptachlor, Lindane, Endosulfan
Air	DDT, BHC
Fodder (Lucerne)	Monocrotophos, Phosphomidon, Endosulfan
Cattle feed	Cypermethrin, DDT, BHC
Pasture and Hay	DDT, Aldrin, Dieldrin, BHC, Heptachlor, Lindan
Rice, wheat flour, oils	DDT, BHC
Dairy Products, Baby milk powder, Butter, Ghee, Cow/buffalo milk	DDT, BHC, HCB, PCB, Heptachlor
Meat, Eggs	DDT, heptachlor, PCB, Carbaryl
Liver, Kidneys, Hair, skin	Cypermethrin
Vegetables	Endosulfan
Adipose tissue of man	BHC, DDT, PCB, HCB, Heptachlor, Aldrin
Human breast milk	BHC, DDT, Aldrin, Heptachlor, HCH
Blood of man	BHC, DDT, Aldrin, Heptachlor, HCH

9. Methods of Elimination of Pesticide Residues

1. Preparatory Steps

- **Washing with Water:** Washing removes surface-bound residues. E.g., 86.2% malathion from okra, 96% from beans.
- **Washing with Salt Solution:** A 2% salt solution removes up to 90.56% of residues in green chilies.
- **Washing with Chemical Solutions:** Chlorinated and ozonated water significantly degrade residues like diazinon and cypermethrin.
- **Peeling and Trimming:** Peeling removes 100% dimethoate and cypermethrin in mango and 70-100% in potatoes.

2. Thermal Treatments

- **Drying:** Oven drying at 80 °C removed 85.5% of etofenprox from spring onions.
- **Blanching:** Blanching spinach reduced residues up to 70%.
- **Baking and Roasting:** Roasting reduced chlorpyrifos by 68.2% in peppers.
- **Pasteurization:** Pasteurization lowered malathion in milk by 44.7%.
- **Boiling, Steaming and Cooking:** Boiling okra reduced malathion by 86.82% and steaming brinjals reduced triazophos by 64-88%.
- **Frying:** Frying reduced residuses in potatoes to <10% for chlorpropham and thiabendazole.

3. Product Manufacturing

- **Juicing and Pureeing:** Apple juice processing removed >90% chlorpyrifos.
- **Drying and Dehydration:** Drying okra reduced malathion by 91.79% and some residues like endosulfan may concentrate.
- **Milling and Baking:** Baking bread reduced malathion by up to 100%, residues concentrated in bran.
- **Canning:** Peaches lost 82.5-95% of residues after peeling and canning.

4. Non-Thermal Technologies

- **Ultrasound:** It effectively disrupts pesticide molecules without harming nutrition.
- **Cold Plasma:** It generates reactive species to degrade pesticide molecules.
- **High-Pressure Processing (HPP):** It preserves vitamins while reducing pesticide load.
- **Refrigeration and Freezing:** Freezing slightly reduces residues but not as effective as thermal methods.
- **Oil refining:** Soybean oil refining removed >80% of organophosphates like chlorpyrifos.

10. Optimization strategies for reducing pesticide residues

Since animals are indirect consumers of pesticides via contaminated fodder, grains or oilseed by-products, mitigation must begin at the source of feed production and continue through the entire value chain.

(i) Good Agricultural Practices (GAP) for Fodder Crops:

Key GAP components include

- Use of recommended pesticides and adherence to label guidelines (dose, dilution, waiting period).
- Avoidance of banned or highly persistent compounds like DDT, aldrin and endosulfan.
- Ensuring pre-harvest interval (PHI) before fodder harvesting to allow for pesticide degradation.
- Farmer education on GAP through extension services, KVKs and cooperatives is essential for ground-level adoption.

(ii) Monitoring and Testing of Feed Ingredients

Routine testing of raw feed materials—especially crop residues (e.g., straw, husk), oilseed cakes, green fodder and commercial feed mixes, is crucial to identify contamination early. Promotion of rapid testing kits (e.g., ELISA-based) at feed mills and procurement centers can facilitate cost-effective screening.

(iii) Use of Biodecontaminants and Binders

Certain natural adsorbents such as activated charcoal, bentonite clay and zeolites, bind to lipophilic pesticide molecules within the gastrointestinal tract, thereby reducing their absorption into the systemic circulation and facilitating their excretion. In addition to physical adsorbents, biological agents such as probiotic bacteria (notably *Lactobacillus* spp.) have shown potential in biodegrading organophosphate and organochlorine pesticides either in the feed itself or during digestion in gut. The strategic inclusion of such biodecontaminants and binders in feed formulations is emerging as a preventive and cost-effective mitigation strategy, particularly in high-risk areas where contaminated crop residues and by-products are commonly used in animal rations.

(iv) Organic and Residue-Free Feed Alternatives

Since these feeds are cultivated without the use of synthetic pesticides or chemical fertilizers, they significantly reduce the contamination entering the food chain. Although organic feeds tend to be more expensive, their use is especially justified in high-value animal categories such as high-yielding dairy cows, breeding bulls and livestock where feed purity and residue-free status are critical for both animal performance and regulatory compliance.

(v) Education, Awareness and Record-Keeping

Farmers should be aware about safe guidelines of using pesticides under the MRLs through training programmes and workshops. Equally important is maintenance of accurate and up-to-date records on pesticide use in fodder crops, including details about chemical types, application timings and harvest intervals.

11. Alternative to Pesticides

Pesticides help in increasing crop yields and reducing manual labour, but their persistence poses significant environmental and health risks. Due to these challenges, regulatory bodies are shifting focus from synthetic pesticides toward biopesticides and other organic alternatives.

Biopesticides

These are microbial products or plant-derived agents that are eco-friendly and pest-specific without causing harm to non-target organisms.

Types of Biopesticides

1. Microbial Biopesticides: Uses micro-organisms such as bacteria, viruses or fungi as active ingredients.

(i) Bacterial Biopesticides

- *Bacillus thuringiensis* (Bt): Effective against lepidopteran pests, is most widely used microbial pesticide.
- *Bacillus subtilis*: Suppresses fungal pathogens and promotes plant growth.

(ii) Fungal Biopesticides

- *Beauveria bassiana*: Controls aphids, whiteflies and other insect pests.
- *Trichoderma spp.*: Effective against soil-borne fungal diseases.

(iii) Viral Biopesticides

- Baculoviruses: Effective against caterpillar pests.

2. Plant-Incorporated Protectants (PIPs): Genetically modified crops that express pesticidal proteins derived from microbes. Like Bt Cotton, Bt Corn, these crops produce Bt toxins internally, reducing the need for external insecticide sprays (Duke *et al.*, 2022) [10].

3. Biochemical/Herbal Pesticides: Natural compounds that affect pest behavior, growth or reproduction.

- **Neem oil:** Contains azadirachtin, which acts as a repellent, antifeedant and growth regulator.

- **Insect pheromones:** Used in mating disruption or trap-based monitoring systems.
- **Essential oils:** Derived from plants like eucalyptus, citronella and clove with known insecticidal properties (Roser and Ritchie, 2017) [24].

Advantages of Biopesticides

Eco-friendly, specific, manage resistance development in pest and low toxicity.

Challenges in Biopesticide Adoption

High production cost, less effective in large-scale use, environmental sensitivity, lesser shelf life and lower adaptability.

12. Conclusions

As excessive and unregulated use of synthetic pesticides has led to serious environmental and health hazards, organic farming offers a sustainable alternative by relying on natural fertilizers, crop rotation and biological pest control instead of synthetic chemicals (Kaur *et al.*, 2019) [17]. It supports ecological balance, soil fertility and food safety, although it may involve yield losses during the initial transition period (Roser and Ritchie, 2017) [24]. Biopesticides, being target-specific and biodegradable, have emerged as a safer substitute with fewer ecological and health risks (Duke *et al.*, 2022) [10]. Also, Integrated Pest Management (IPM) a hybrid system combining the strengths of both organic and conventional methods ensures higher productivity while safeguarding human health and environmental sustainability (Tudi *et al.*, 2021) [25].

In conclusion, a balanced approach integrating modern science with traditional wisdom is essential for achieving safe, healthy and resilient food systems and sustainable agricultural practices. (Kaur *et al.*, 2019) [17].

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